Strength of Reinforced Concrete Columns with Transverse Openings

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ABSTRACT

The present work is concerned with the investigation of the behavior and ultimate capacity of axially loaded reinforced concrete columns in presence of transverse openings under axial load plus uniaxial bending. The experimental program includes testing of twenty reinforced concrete columns (150 × 150 × 700 mm) under concentric and eccentric load. Parameters considered include opening size, load eccentricity and influence of the direction of load eccentricity with respect to the longitudinal axis of the opening. Experimental results are discussed based on load – lateral mid height deflection curves, load – longitudinal shortening behavior, ultimate load and failure modes. It is found that when the direction of load eccentricity is parallel to the longitudinal axis of openings, column behavior is more pronounced when than the direction is normal to the longitudinal axis of openings.

Keywords: RC Columns, Transverse Openings, Load eccentricity, Ultimate Load.

تحمل الأعمدة الخرسانية المسلحة ذات الفتحات المستعرضة

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الخلاصة

ان البحث الحالي يتركز على دراسة السلوك الانشائي وقابلية تحمل الاعمدةالخرسانية المسلحة المحملة محوريا بوجود الفتحات مستعرض تحت تاثير الاحمال المحورية والعزوم احادية الاتجاه .يتضمن البرنامج العملي من هذا البحث فحص عشرون عموداً خرسانياً مسلحاً ذات مقطع مربع بابعاد 150×150) ملم (وبطول700) ملم .(تضمنت المتغيرات الأساسية التي جرى إعتمادها حجم الفتحة ,اللامركزية للحمل وتاثير اتجاه اللامركزية للحمل بالنسبة الى اتجاه المحور الطولي للفتحة .نوقشتْ نَتائِج الفحص على أساس سلوك الحملِ - الهطول الجانبيِ عند منتصف العمود وسلوك الحملِ - القصر الطوليِ والحمل الأقصى وأنماط الفشلِ .وجد من النتائج العملية عندما يكون لاتمركزية الحمل موازية لاتجاه المحور الطولي للفتحة يكون تصرف العمود بصورة افضل عندما يكون الاتجاه متعامد على المحور الطولي للفتحة.

الكلمات المفتاحية :الاعمدة الخرسانية المسلحة, الفتحات المستعرضة ,لامركزية التحميل ,الحمل الاقصى.

INTRODUCTION

Transverse openings may present in reinforced concrete columns as access for services including plumbing pipes and electrical conduits. The presence of these openings results in reduction of strength and stiffness and of the columns. If the presence of such openings is negligible during the design these stage, structural damage may occurred. **Lotfy, 2013,** conducted a nonlinear finite element analysis on 21 reinforced concrete column specimens using, **ANSYS, 2010,** software version 10 to study the strength loss due to presence of transverse holes in columns. The parameters considered were dimensions, shapes and positions of the holes. A comparison between the available experimental results and finite element analysis is presented. It was found that results and conclusions may be useful for designers.

Hassan, Sarsam and **Allawi , 2013, 2015,** studied the behavior of reinforced concrete columns under uniaxial and biaxial bending. Their works deal with strengthening of columns by using carbon fiber reinforced polymer (CFRP). The experimental program includes testing of eight reinforced concrete columns (150×150×500mm) tested under several load conditions. The considered variables are the effect of both eccentricity and longitudinal reinforcement (Ø12mm or Ø6mm). Test results are discussed based on lateral and longitudinal deflection behavior, ultimate load and failure modes. The CFRP strengthening shows a complete change in the failure mode of the columns. Also, they concluded that the effect of longitudinal reinforcement in the case of uniaxial and biaxial bending is more effective for strengthened columns than for unconfined columns.

The ACI building Code ACI 318-2014 stated that "Conduits and pipes, with their fittings, embedded within a column shall not occupy more than 4% of the cross-sectional area on which strength is calculated". Experimental tests dealing with the effect of presence of transverse openings inside columns is arrived out in the present study to investigate the strength reduction for concentric and eccentric loaded columns. Also, the influence of transverse openings on the behavior and mode of failure of the tested columns is investigated.

Al-Sali , 2015, studied the behavior and the load carrying capacity of reinforced concrete short columns having different types of transverse openings. The experimental program deals with the ultimate strength of tested columns. The variables considered in the experimental work include shapes of openings having the same opening ratio of 0.133. The tested columns have been also analyzed using a nonlinear finite element model. An increase in the ultimate strength of about 2.06% is achieved when single opening of 20 mm diameter is replaced by two symmetrical openings of 10 mm diameter each. Also, a decrease in the ultimate strength of about 2.88% and 5.97% is observed when the single circular opening of 20 mm diameter is replaced by 20×20 mm square opening or 20×40 mm rectangular opening respectively.

EXPERIMENTAL PROGRAM

Column specimens having an overall height of 900 mm and a square cross section of (150 mm × 150 mm) are considered. The transverse openings are positioned at mid height of the columns as shown in **Fig. 1**. The opening ratio is calculated as the projecting area of the opening at the opening level (i.e. at mid height of column) divided by the column cross sectional area. Reinforcing steel bars provided for all columns are 4Φ10 mm longitudinal, and hence, the steel ratiois 1.4%, which lies within the ACI 318-14 Code limitations. The transverse closed bars are consisted of Φ6 mm @ 100 mm as shown in **Fig. 2.**

Test length is considered as the middle part of the column having a 700 mm height. The remaining 100 mm upper and lower parts of the column are positioned inside the upper and lower steel caps to apply the moments at the ends as shown in **Fig. 3**. This configuration is adopted to prevent possible failure at the ends. Also, the embedded ends help to stabilize the specimen throughout the testing procedure.

IDENTIFICATION OF SPECIMENS

To identify test specimens with different sizes of openings and eccentricities direction, the following designation system is suggested:

- **Group numbering:** The first character is used to identify the group number. C1 refers to specimens of group A in which the eccentricity is applied in direction parallel to the longitudinal axis of openings, and C2 refers to columns of group B in which eccentricity is applied in direction normal to the longitudinal axis of openings.
- **Opening Size:** The second character is used to identify the size of opening. Φ0 refers to columns without opening, Φ15 refers to opening of 15 mm diameter, Φ20 refers to opening of 20 mm diameter and Φ25 refers to opening of 25 mm diameter.
- **Load eccentricity:** The third character is used to specify the values of load eccentricity. E0 refers to axially loaded columns. 45 refer to 45 mm loading eccentricity and E120 refers to 120 mm loading eccentricity.

Table 1 gives specimens designation system and opening details.

MATERIALS PROPERTIES

For each group, three standard cylinders (100×200mm) were tested to obtain the compressive strength ($f_c^{'}$), splitting tensile strength (f_{ct}) (ASTM standard C496) and static modulus of elasticity (E_c) at 28 days (ASTM standard C469) and at time of testing using a universal testing machine. The standard mechanical properties of hardened concrete are listed in **Table 2**.

For all columns, two sizes of steel reinforcing deformed bars were used. Bars of size (Φ10 mm) were used as longitudinal reinforcement and bars of size (Φ6 mm) were used as closed stirrups. Values for yield stress and ultimate strength are obtained according to ASTM standard A615 requirements for each bar size and are given in **Table 3**.

TESTING PROCEDURE

A. Steel Caps

According to the previous researches, a precise load eccentricity using is difficult to obtain. **Hadi , 2007,** concluded that the position of the applied load was not accurate and the columns had a tendency to break at the tested connection region. Therefore, eccentric loading was simulated by designing a new steel end caps to allow the eccentric load to be accurately positioned prior to testing of the circular columns. **Ranger** and **Bisb , 2007,** used steel collars (caps) to fix their tested columns and to ensure stability and accurate eccentric loading during testing. In the present work, new two loading end caps were designed and implemented. In case of eccentric loading, each loading cap was consisted of four Φ20 mm holes at the base of the cap through which the threaded part of the longitudinal reinforcement is passed to ensure adequate length of development. In addition, each side of loading cap includes three M24 female threads with bolts. These bolts were used to fasten the loading cap together with the column through the available four (5×100×148 mm) steel plates. These plates were used to prevent the column from damaging when the M24 bolts are tightened to the column specimen. Another two (5×150×150mm) steel plates were used at the top and bottom of the tested column before placing the loading caps to protect the column during the test and to distribute the applied loading across column cross section. **Fig. 4** shows the steel caps and **Fig. 5** represents a schematic representation with details.

B. Measurements and Instrumentation

In case of concentrically loaded columns, axial deformation was recorded using two dial gages at two opposite sides of specimen over a length of 700 mm as shown in **Fig. 6**. While for the eccentrically loaded columns, three additional dial gages were used to monitor the lateral displacement for each specimen. The location of these dial gages were at mid height and at 320 mm above and below mid height.

The average reading of the upper and lower dial gages has been subtracted from the reading of the middle dial gage to obtain the net lateral displacement. Also, the axial deformations were recorded using three dial gages over a length of 700mm of the eccentric columns. These dial gages were fixed to the steel caps at different locations as shown in **Fig. 7**.

Also, a linear variable differential transformer (LVDT) is used to measure the axial displacement across the opening by fixing it at two points on the tension face of the specimen and the data of LVDT is recorded for each stage of loading as shown in **Fig. 8**.

C. Supporting System

The stability of the columns during testing is the main difficulty especially in case of high value of eccentricity. Therefore, a supporting system was designed to stabilize the specimens during testing. This system is consisted of four bolts located at the top and the bottom ends in touch with the caps by using steel balls located at the ends, **Fig. 9**.

The benefit of these steel balls is to assure that the supporting system does not influence the carrying capacity of the column and to prevent the possible horizontal movement of specimen at ends. In addition, this system allows movement of column inside the machine to achieve the precise eccentricity and allows the longitudinal movement of specimen to occur.

D. Loading Technique

A new loading system has been developed to apply the precise eccentric loading. This system comprised a steel shaft with half spherical hole at its end, Φ45 mm steel ball and (10×90×90 mm) square plate with a sector of spherical hole located at its middle as shown in **Fig. 10**. The steel shaft can moves vertically inside a steel ring which prevents the shaft from horizontal sliding during loading as shown in **Fig. 11**.

The location of this ring is at the center of testing machine at upper and lower bases. This technique ensures that the load has a fixed loading.

E. Testing Procedure of the Columns Specimens

The testing machine shown in **Fig. 12** has a capacity of 2000 kN. The load was gradually applied and at each increment loasing, readings were recorded. In the trial test, the column was loaded up to failure. The recorded data was analyzed to ensure the working conditions of all the instrumentation used and the safety of testing procedure. After performing the trial test, the scheduled tests were carried out.

The testing procedure is summarized as follows:

- Locating the column specimens inside the lower cap and then the upper cap was placed; All the bolts were properly fastened.
- Lifting the column to the slide steel base level then sliding it into the testing machine as shown in **Fig. 13**.
- Releasing the bolts of the loading cap.
- Applying concentric force to insure full contact between column and loading caps and tightening all the bolts, then the applied load is removed.
- By using the supporting system, the column moves horizontally until reaching the precise required eccentricity.
- The longitudinal bars were tightened to the loading caps especially in cases of eccentric loading that may undergo tension.
- Applying fixation load then all dial gages are fixed and initial reading were recorded.
- The load was gradually applied in increments. At each load increment, all readings were acquired manually.

EXPERIMENTAL RESULTS

A. Ultimate Strength Results

A.1: Group A (Load eccentricity in the direction parallel to the longitudinal axis of openings)

Foe all columns of group A, experimental ultimate strength values are shown in **Table 4**. These columns have been tested under axial compressive load or axial load with 45 mm and 120 mm eccentricity values in the direction parallel to the longitudinal axis of opening. For tested columns of this group, in which zero eccentricity and different opening ratios of (0.00%, 10.00%, 13.33%, and 16.67%) were used, a significant reduction in ultimate strength is noticed due to the significant reduction in compression area. The percentage decrease in the ultimate strength compared to column C1Φ0E0 (reference column) were 3.21%, 5.02% and 6.22% for columns C1Φ15E0, C1Φ20E0 and C1Φ25E0 respectively.

For the tested columns of this group, in which 45 mm eccentricity was exist with the same different opening ratios shown above (0.00%, 10.00%, 13.33%, and 16.67%), a significant reduction in the ultimate strength is observed since the opening area is located within the compression zone for column cross section which reduces the compression area. The low eccentricity ratio (e/h=0.3) for these columns makes the compression failure mode to be the dominant mode and no yielding of tension reinforcement was occurred. The percentage decrease in the ultimate strength compared to

column C1Φ0E45 (reference column) were 6.36%, 10.46% and 12.27% for columns C1Φ15E45, C1Φ20E45 and C1Φ25E45 respectively.
For tested columns of this group, in which 120mm eccentricity was exist and different opening ratios of (0.00%, 10.00%, 13.33%, and 16.67%),an insignificant reduction in the ultimate strength is noticed due to the large eccentricity ratio (e/h=0.8). The cracks in these columns at the tension face are formed and the effect of bending moment is more pronounced than the effect of the axial compressive load. The percentage decrease in the ultimate strength compared to column C1Φ0E120 (reference column) were 1.51, 1.51and 2.14 for columns C1Φ15E120, C1Φ20E120 and C1Φ25E120 respectively as shown in **Fig. 14**.

A.2 Group B (Load eccentricity in the direction normal to the longitudinal axis of openings)

For all columns of group B, experimental ultimate strength values are given in Table 4. These columns were tested under axial compressive load with 45 mm and 120 mm eccentricity values in the direction normal to the longitudinal axis of opening. For tested columns of this group, in which 45mm eccentricity was exist and different opening ratios of (0.00%, 10.00%, 13.33%, and 16.67%) were used, an insignificant reduction in the ultimate strength is observed since the opening area is not located within the compression zone of the column cross section as shown in **Fig. 15**.

The percentage decrease in the ultimate strength compared to column C3Φ0E45 (reference column) are 0.44, 0.85 and 1.31 for columns C2Φ15E45, C2Φ20E45 and C2Φ25E45 respectively. For tested columns of this group, in which 120mm eccentricity was exist and different opening ratios of (0.00%, 10.00%, 13.33%, and 16.67%) were used, a relatively insignificant decrease in the ultimate strength is noticed, as shown in **Fig. 14.** due to the large eccentricity ratio (e/h=0.8). The cracks in these columns at the tension face are formed and the effect of the bending moment is more pronounced than the effect of the axial compressive load.

B. Effect of Transverse Openings on the Load-Deflection Behavior

B.1: Concentrically Loaded Columns

The experimental behavior of load versus axial shortening behavior of the columns of group A, in which 0.0 mm eccentricity is used, are presented in **Fig. 16**. It can be noticed that the effect of presence of transverse openings are significant because of the total opening area lies within the column compression zonea. Also, it is evident that the increase in the opening area causes a reduction in the ultimate load and increases the deflection at the ultimate load level.

B.2 Eccentrically loaded columns

B.2.1 Load eccentricity equal to 45 mm

Figs. 17 to 22 illustrate the influence of the presence of transverse openings on the load versus vertical deflection response of the columns and lateral mid-height deflection curves of columns of group A and two in which 45 mm loading eccentricity is used. For tested columns of group A most of opening area lies within the column compression area that leads to a reduction in the ultimate load values in addition to an increase in deflection at ultimate load level. This is due to the reduction in stiffness and moment of inertia of the columns as the opening area increases. Also, one can conclude from Figs. 17 to 22 that the effect of eccentricity of loading in direction parallel to the longitudinal axis of openings (specimens of group A) is more than that of the direction when it is normal to the longitudinal axis of openings (specimens of group B). This is because the opening is existed in compression zone in case of parallel direction of opening axis and loading eccentricity while this not find in the other case.

B.2.2 Load Eccentricity Equal to 120 mm

Figs. 23 to 28 show the effect of the presence of transverse openings on the load versus vertical deflection response of the columns and lateral mid-height deflection curves of columns of group A and two in which 120 mm loading eccentricity is used. From these figures, it is clear that the increase in transverse opening size has a negligible effect on the ultimate load capacity. However, the increase in opening ratio affects deflection values at the ultimate load because the increase in opening ratio leads to a reduction in column stiffness.

C. Effect of Eccentricity on the Behavior of Reinforced Concrete Columns with Transverse Openings

To study the effect of eccentricity of loading on the response of reinforced concrete columns having transverse openings, eight columns of group A and eight columns of group B were tested with two values of e/h (0.3 and 0.8).

C.1 Group A (load eccentricity in the direction parallel to the longitudinal axis of openings)

For group A and for columns having zero opening ratio (solid columns), the behavior of specimen C1Φ0E45 is compared with that of specimen C1Φ0E120 using the load versus vertical and lateral mid-height deflections as shown in **Fig. 29** and **Fig. 30**. The ratio of ultimate capacity of column C1Φ0E120 to that of column C1Φ0E45 is 0.3.

For same group and for columns having 0.1 opening ratio, the behavior of specimen C1Φ15E45 is compared with that of specimen C1Φ15E120 using the load versus vertical and lateral mid-height deflections as shown in **Fig. 31** and **Fig. 32**. The ratio of ultimate capacity of column C1Φ15E120 to that of column C1Φ15E45 is 0.32. For columns having 0.133 opening ratio, the behavior of specimen C1Φ20E45 is compared with that of specimen C1Φ20E120 using the load versus vertical and lateral mid-height deflections as shown in **Fig. 33** and **Fig. 34**. The ratio of ultimate capacity of column C1Φ20E120 to that of column C1Φ20E45 is 0.33.

Finally, for the same group and for columns having 0.167 opening ratio, the behavior of specimen C1Φ25E45 is compared with that of specimen C1Φ25E120 using the load versus vertical and lateral mid-height deflections as shown in **Fig. 35** and **Fig. 36**. The ratio of ultimate capacity of column C1Φ25E120 to that of column C1Φ25E45 is 0.33.

C.2 Group B (load eccentricity in the direction normal to the longitudinal axis of openings)

For group B and for columns having zero opening ratio (solid section), specimen C3Φ0E45 is compared with specimen C3Φ0E120 using the load versus vertical and lateral mid-height deflections as shown in **Fig. 37** and **Fig. 38**. The ratio of ultimate capacity of column C3Φ0E120 to that of column C3Φ0E45 is 0.287.

For the same group and for columns of 0.1 opening ratio, specimen C3Φ15E45 is compared with specimen C3Φ15E120 using the load versus vertical and lateral mid-height deflections as shown in **Fig. 39** and **Fig. 40**. The ratio of ultimate capacity of column C3Φ15E120 to that of column C3Φ15E45 is 0.288.

For columns having 0.133 opening ratio, specimen C3Φ20E45 is compared with specimen C3Φ20E120 using the load versus vertical and lateral mid-height deflections as shown in **Fig. 41** and **Fig. 42**. The ratio of ultimate capacity of specimen C3Φ20E120 to that of specimen C3Φ20E45 is 0.289.

Finally, for the same group and for columns of 0.167 opening ratio specimen C3Φ25E45 is compared with specimen C3Φ25E120 using the load versus vertical and lateral mid-height deflections as shown in **Fig. 43** and **Fig. 44**. The ratio of ultimate load of column C3Φ25E120 with respect to that obtained for column C3Φ25E45 is 0.290.

TEST OBSERVATIONS

Images of selected tested concentrically and eccentrically loaded columns of groups A and B are shown through **Figs. 45 to 50**.

For all concentrically loaded columns shown in **Figs. 45 and 46**, one can noticed that the appearance of vertical cracks in concrete cover at the middle third zone of the specimen was always the first sign of failure and cracks in all specimens with opening were noticed. They were generated in a diagonal direction around the openings and growth to concur with the vertical cracks then these cracks spread rapidly after spalling of concrete cover. At this stage, the concrete core carries the applied axial load due to the coupling confinement effect of ties and longitudinal bars.

Failure is occurred in a brittle and explosive manner, where the longitudinal bars buckled and a crush occurred in concrete at section of the opening and this section was separated into two sliding surfaces. For all loaded specimens with 45mm eccentricity shown in **Figs. 47** and **48**, it can be noticed that crushing of concrete was observed on the compression face of the columns at the middle third zone of the specimen and few number of horizontal cracks in this zone initiated at the tension face of the column. Some of these cracks pass through the opening and progress starting from tension to compression faces. At later stage, the concrete cover firstly spalled off followed by buckling of the longitudinal bars and a loss of strength was immediately observed after reaching the peak load.

For all loaded columns with 120mm eccentricity shown in **Figs. 49** and **50**, one can noticed that a large number of distributed horizontal cracks occurred at the tension face along the column. Also, these cracks extended to the side faces of tested column especially at the middle third of specimen length. These cracks are wider than the cracks at loaded columns with 45mm eccentricity. At a later stage, the strength of specimen stood constant after reaching the peak value with a rapid increase in crack width at tension face. Then concrete cover spalled off at the compression face and a loss of strength was immediately observed after the peak load is reached.

CONCLUSIONS

According to the experimental tests carried out in this research work, the following conclusions can be drawn:

1. The presence of transverse openings in reinforced concrete columns reduces the ultimate load strength. For columns subjected to pure compressive axial load, the experimental results showed a reduction in ultimate strength ranging between 3.21% and 6.22%.
2. For columns in which the load eccentricity is applied in the direction parallel to the longitudinal axis of opening and tested with eccentricity equal to 45mm (e/h=0.3), the experimental results showed a reduction in strength ranging between 6.36% and 12.27%, while for eccentricity equal to 120mm (e/h=0.8), the experimental results showed that insignificant reduction in ultimate strength can occur.
3. The experimental results showed that insignificant reduction is occurred for both eccentricities 45 and 120 mm for columns in which the load eccentricity is applied in the direction normal to the

longitudinal axis of opening. Noting that, the above range of strength reduction is corresponding to opening ratios ranging between 10.0 % and 16.67%.

4. It was found that the load eccentricity has a significant effect on the load deflection curve and the ultimate strength value of the uniaxially loaded columns. The experimental results showed that when load eccentricity increases the ultimate load is considerably decreased.
5. For tested columns in which the eccentricity is applied in the direction parallel to the longitudinal axis of opening, an increase in the eccentricity from 45 mm to 120 mm causes a decrease the ultimate strength by about 70%, 68.45%, 67% and 66.54% for opening ratios of 0.0%, 10.00%, 13.33% and 16.67% respectively.
6. For tested columns in which the eccentricity is applied in the direction normal to the longitudinal axis of opening an increase in the eccentricity from 45 mm to 120 mm causes a decrease the ultimate strength by about 71.31%, 71.18%, 71.05% and 70.93% for opening ratios of 0.0%, 10.0%, 13.33% and 16.67% respectively.

REFERENCES

- Al-Salim, N. H., 2015, Behavior and Stress Analysis around Openings for Reinforced Concrete Columns, International Journal of Chemical, Environmental & Biological Sciences (IJCEBS) Vol. 3, Issue 5, ISSN 2320–4087 (Online), pp. 404 – 407.
- ASTM A615 / A615M - 16, Standard specification for deformed and plain carbon-steel bars for concrete reinforcement, Annual Book of ASTM, vol. 01.04.
- ASTM C469 / C469M – 14 Standard test method for static modulus of elasticity and poisson's ratio of concrete in compression Annual Book of ASTM, vol. 04.02.
- ASTM C496 / C496M – 11 Standard test method for splitting tensile strength of cylindrical concrete specimens Annual Book of ASTM, vol. 04.02.
- Building Code Requirements for Structural Concrete. (ACI 318-14), and Commentary (ACI 318R- 14), American Concrete Institute, Farmington Hills, Michigan 2014.
- Hadi, M.N.S. (2007), Behavior of FRP wrapped circular concrete columns under eccentric loading, University of Patas, Patas, Greece, July 16-18, pp.10.
- Hassan, R. F., Sarsam, K. F, and Allawi, A. A. 2013, Behavior of strengthened RC columns with CFRP under biaxial bending, University of Baghdad Engineering Journal, Vol. 3, No. 9, ISSN 1726 –4073, pp. 1115-1126.
- Hassan, R. F., Sarsam, K. F, and Allawi, A. A. 2015, Behavior of strengthened RC short columns with CFRP under eccentric load, THE 7TH ASIA PACIFIC YOUNG RESEARCHERS AND GRADUATES SYMPOSIUM, "Innovations in Materials and Structural Engineering Practices, Malaysia, Kuala Lumpur.
- Installation Guide 2010, ANSYS – VERSION -10, Computer Software for structural engineering.
- Lotfy, F. M., 2013, Nonlinear analysis of reinforced concrete columns with holes, International Journal of Civil and Structural Engineering, Vol. 3, No. 3, ISSN 0976-4399, pp. 655-668.
- Ranger, M., and Bisby, L., Effect of load eccentricities on circular FRP-confined reinforced concrete columns, University of Patas, Patras, Greece, July 16-18, 2007, pp.10.

Table 1. Designation of tested columns.

Group	Column designation	e/h	Opening size, mm	Opening ratio, %
A	C1Φ0E0	0.0	0.0	0.0
	C1Φ0E45	0.3	0.0	0.0
	C1Φ0E120	0.8	0.0	0.0
	C1Φ15E0	0.0	15	10
	C1Φ15E45	0.3	15	10
	C1Φ15E120	0.8	15	10
	C1Φ20E0	0.0	20	13.33
	C1Φ20E45	0.3	20	13.33
	C1Φ20E120	0.8	20	13.33
	C1Φ25E0	0.0	25	16.67
	C1Φ25E45	0.3	25	16.67
	C1Φ25E120	0.8	25	16.67
B	C3Φ0E45	0.3	0.0	0.0
	C3Φ0E120	0.8	0.0	0.0
	C3Φ15E45	0.3	15	10
	C3Φ15E120	0.8	15	10
	C3Φ20E45	0.3	20	13.33
	C3Φ20E120	0.8	20	13.33
	C3Φ25E45	0.3	25	16.67
	C3Φ25E120	0.8	25	16.67

Table 2. Mechanical properties of hardened concrete, MPa.

Test	Experimental	Standard specification	Note
Comp. strength	30.8 for group A 31.3 for group B	---	---
Splitting tensile strength	3.0 for group A 3.01 for group B	3.11 3.13	
Modulus of elasticity	25325 for group A 25703 for group B	26083 26295	

Table 3. Steel bars properties.

Nominal diameter, mm	Actual Diameter, mm	Yield Stress f_y, MPa	Ultimate Strength f_u, MPa	Modulus of Elasticity E_s, GPa
6	5.74	533	565	195.9
10	10.03	549	621	196.6

Table 4. Ultimate strength capacity of all tested columns.

Group	Column designation	Experimental ultimate load, kN	Reduction in ultimate strength, %
A	C1Φ0E0	1034.6	Ref. column
	C1Φ0E45	457.0	Ref. column
	C1Φ0E120	137.1	Ref. column
	C1Φ15E0	1001.4	-3.21
	C1Φ15E45	428	-6.36
	C1Φ15E120	135	-1.51
	C1Φ20E0	982.7	-5.02
	C1Φ20E45	409.5	-10.46
	C1Φ20E120	135.0	-1.51
	C1Φ25E0	970.2	-6.22
	C1Φ25E45	400	-12.27
	C1Φ25E120	134.2	-2.14
B	C3Φ0E45	477.8	Ref. column
	C3Φ0E120	137.1	Ref. column
	C3Φ15E45	475.8	-0.44
	C3Φ15E120	137.1	0.00
	C3Φ20E45	473.7	-0.85
	C3Φ20E120	137.1	0.00
	C3Φ25E45	471.6	-1.31
	C3Φ25E12	137.11	0.00

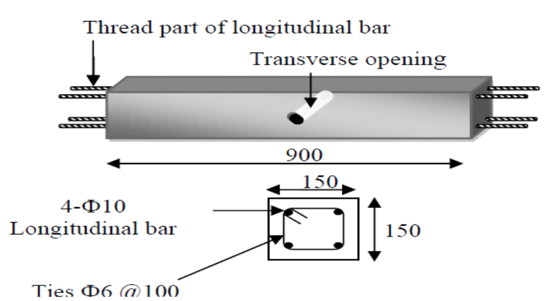


Figure 1. Dimensions and reinforcement details of column specimen.

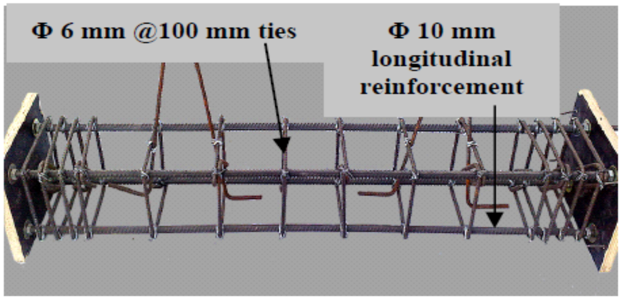


Figure 2. Details of column reinforcement

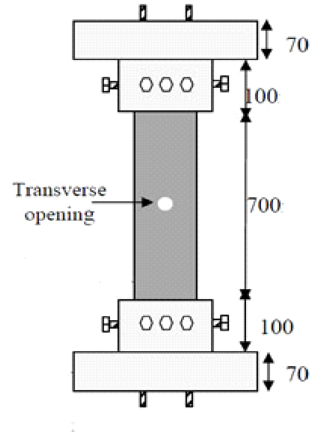


Figure 3. Specimen details and dimensions

Figure 4. Details of loading steel cap

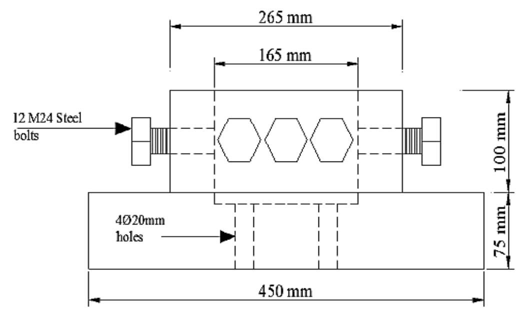


Figure 5. Schematic representation for loading steel cap

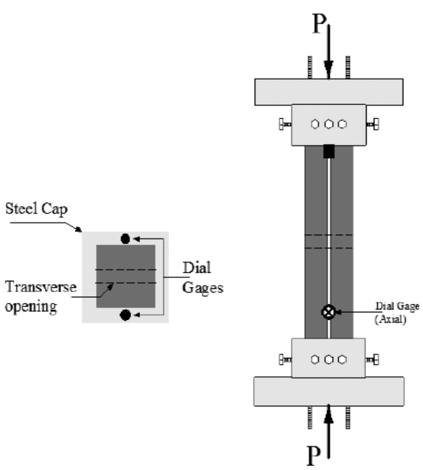


Figure 6. Schematic representation for dial gage positions mounted on concrete columns.

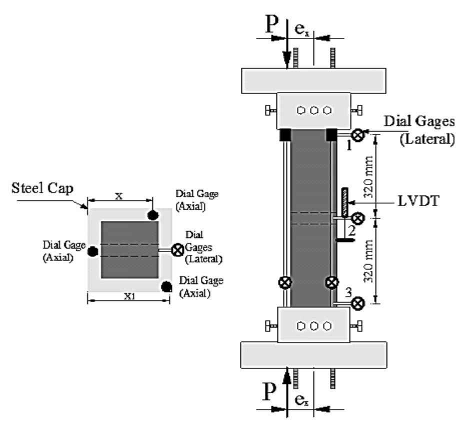


Figure 7. Schematic representation for dial gage position mounted on eccentric loaded columns.

Figure 8. LVDT use to measure axial displacement.

Figure 9. Supporting system used at columns ends.

Figure 10. Loading steel shaft details.

Figure 11. Steel shaft inside the details.

Figure 12. Testing machine used in the present work **.**

Figure 13. Lifting of tested column to the slide steel base level.

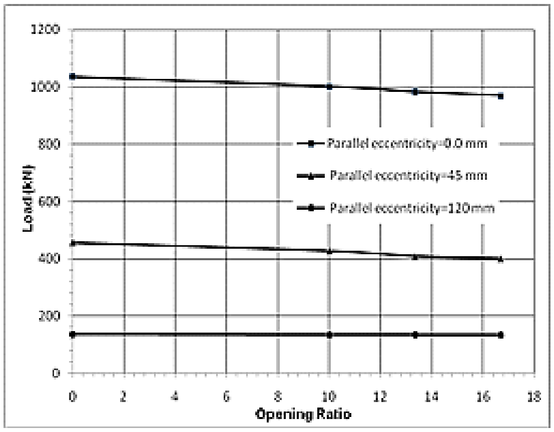


Figure 14. Effect of the opening ratio on the ultimate strength of columns of group A

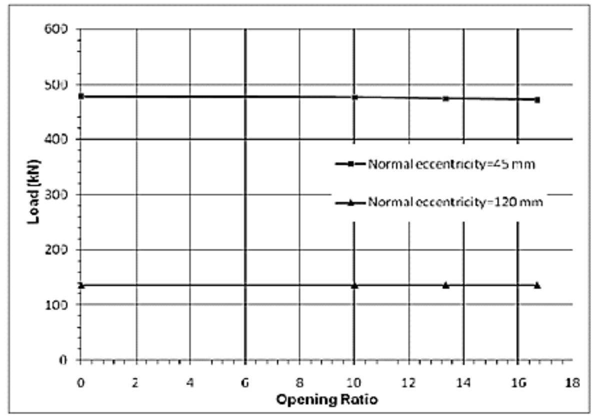


Figure 15. Effect of the opening ratio on the ultimate strength of columns of group B

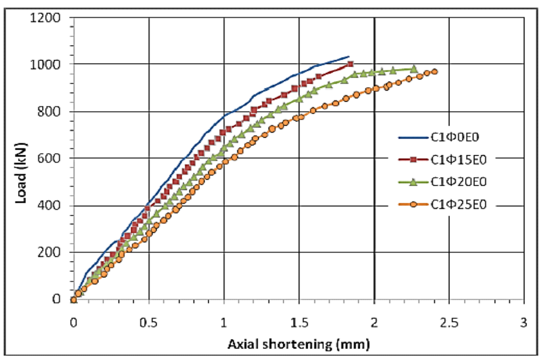


Figure 16. Load versus axial shortening for columns of group A, e = 0.0 mm

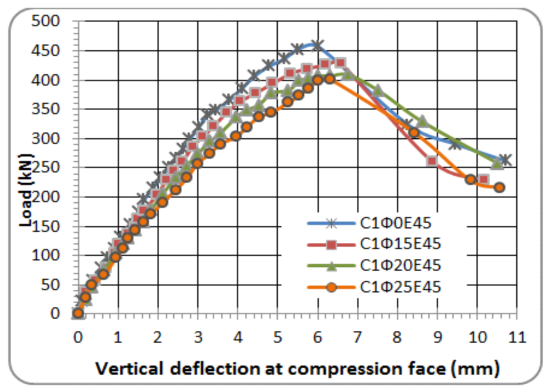
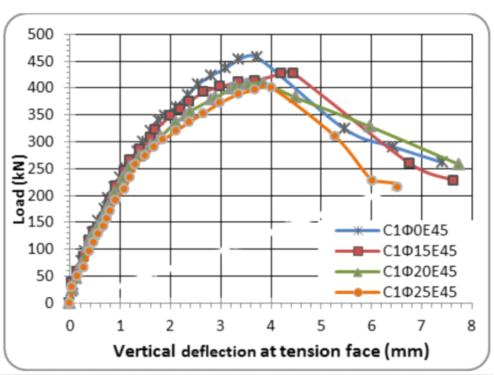


Figure 17. Load versus vertical deflection at compression face of columns of group A, e=45 mm



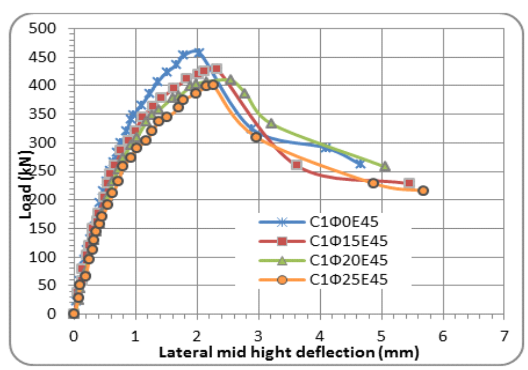


Figure 18. Load versus lateral mid height deflection of columns of group A, e=45 mm

Figure 19. Load versus vertical deflection at tension face of columns of group A, e=45 mm

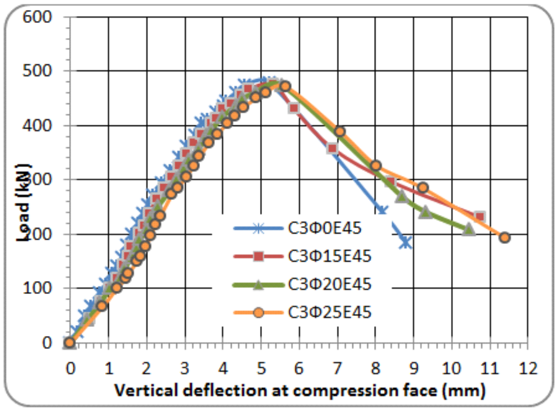


Figure 20. Load versus lateral mid height deflection of columns of group B, e=45 mm

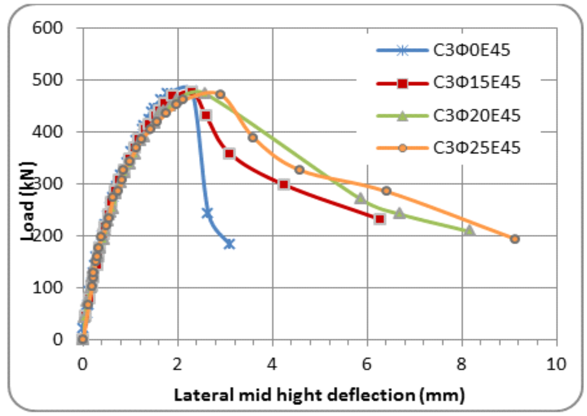


Figure 21.Load versus vertical deflection at tension face of columns of group B, e=45 mm

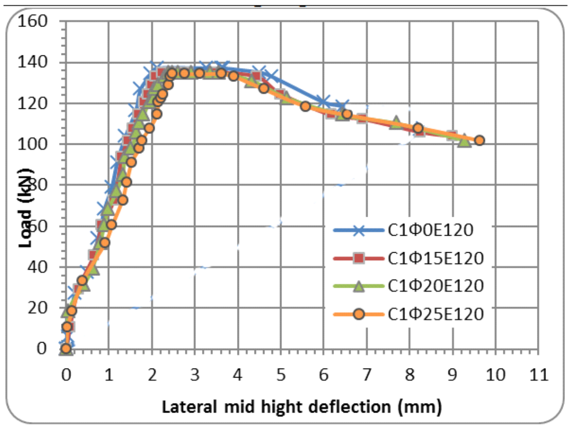


Figure 22. Load versus vertical deflection at tension face of columns of group B, e=45 mm

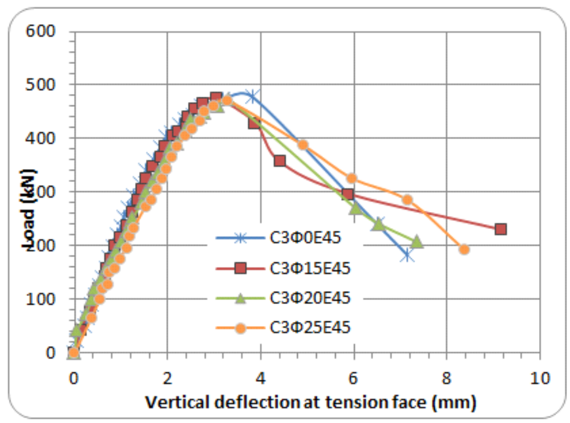


Figure 23. Load versus lateral mid height deflection of columns of group A, e=120 mm

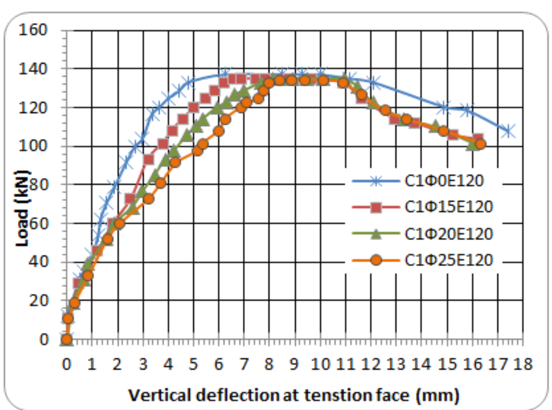


Figure 24. Load versus vertical deflection at compression face of columns of group A,e=120mm

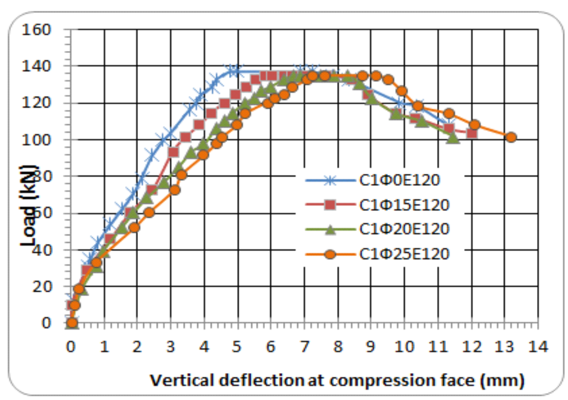


Figure 25. Load versus vertical deflection at tension face of columns of group A,e=120mm

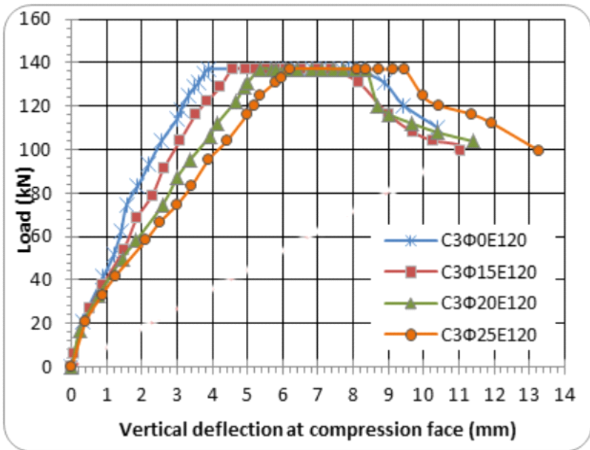


Figure 26. Load versus lateral mid height deflection of columns of group B,e=120mm

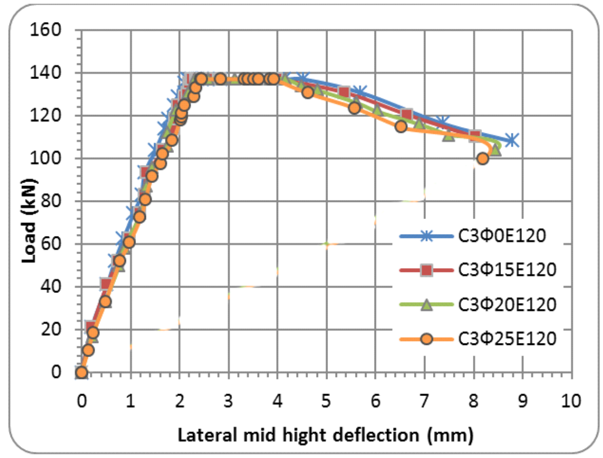


Figure 27. Load versus vertical deflection at compression face of columns of group B,e=120mm

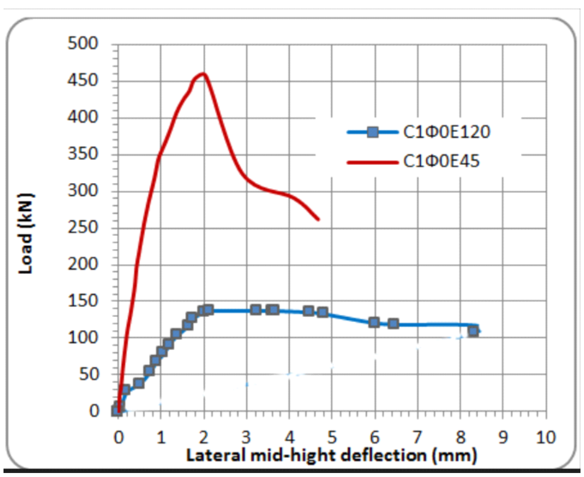


Figure 28. Load versus vertical deflection at tension face of columns of group B, e=120 mm

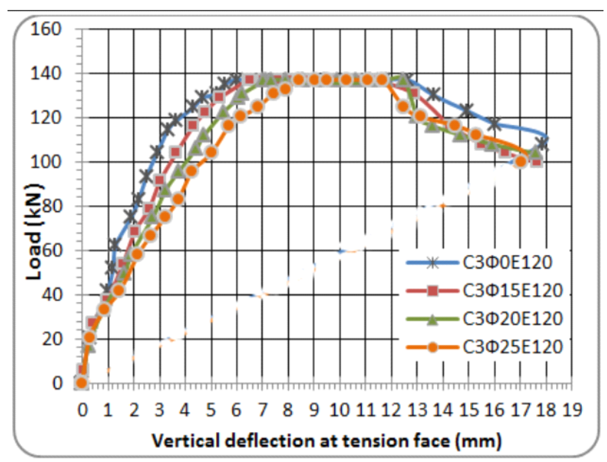


Figure 29. Load versus lateral mid-height deflection for columns C1Φ0E120 and C1Φ0E45

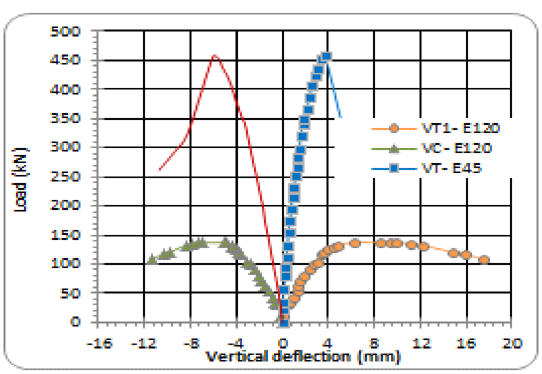


Figure 30. Load versus vertical deflection for columns C1Φ0E120 and C1Φ0E45

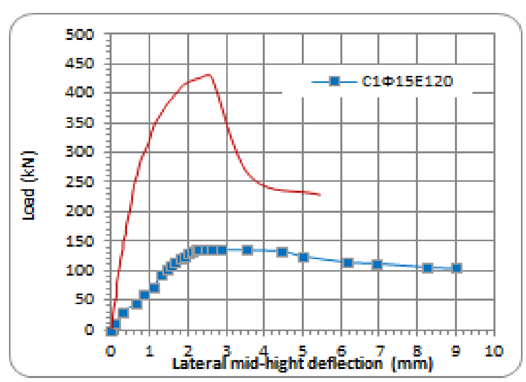


Figure 31.Load versus lateral mid-height deflection for columns C1Φ15E120 and C1Φ15E45

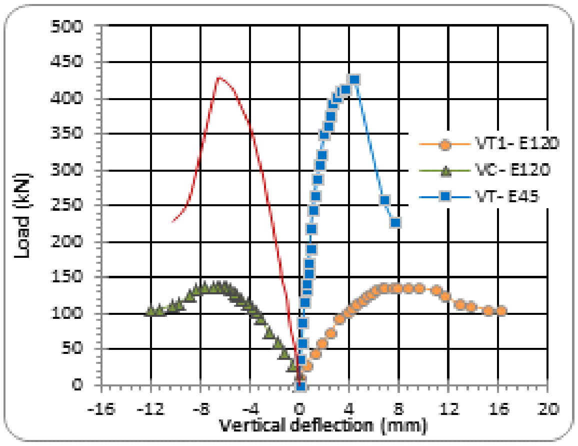


Figure 32. Load versus vertical deflection for columns C1Φ15E120 and C1Φ15E45

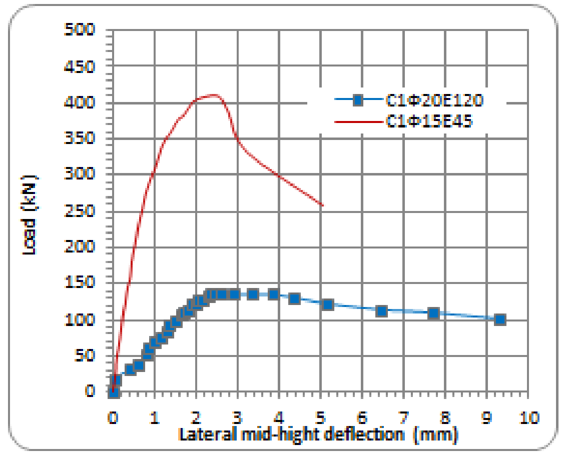


Figure 33. Load versus lateral mid-height deflection for columns C1Φ20E120 and C1Φ20E45

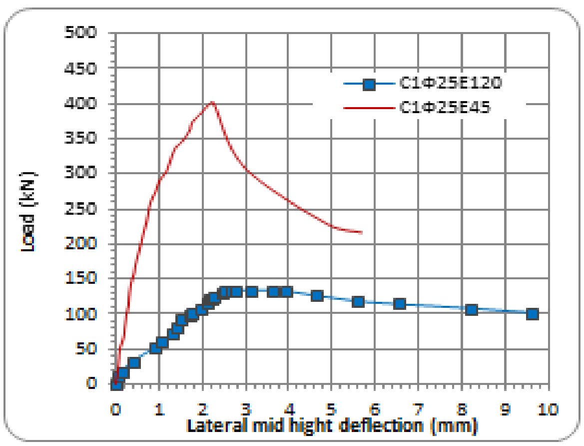


Figure 34. Load versus vertical deflection for columns C1Φ20E120 and C1Φ20E45

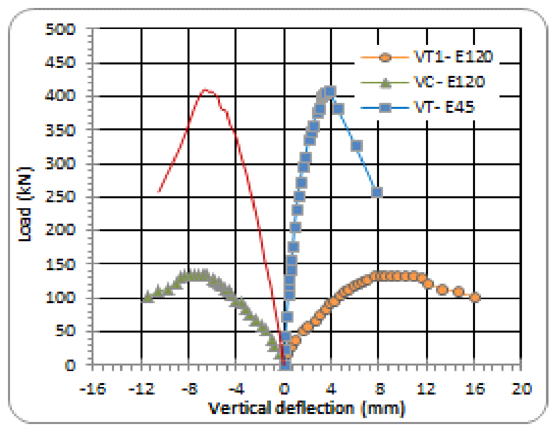


Figure 35. Load versus lateral mid-height deflection for columns C1Φ25E120 and C1Φ25E45

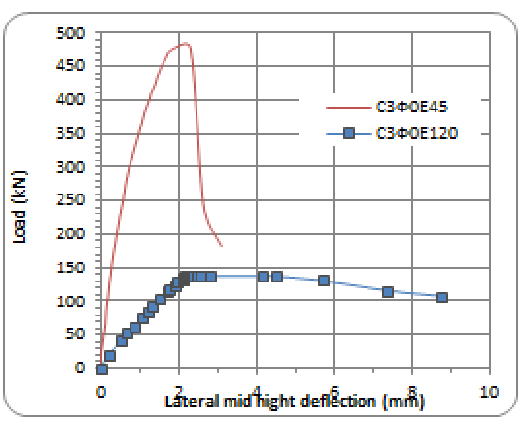


Figure 36. Load versus vertical deflection for columns C1Φ25E120 and C1Φ25E45

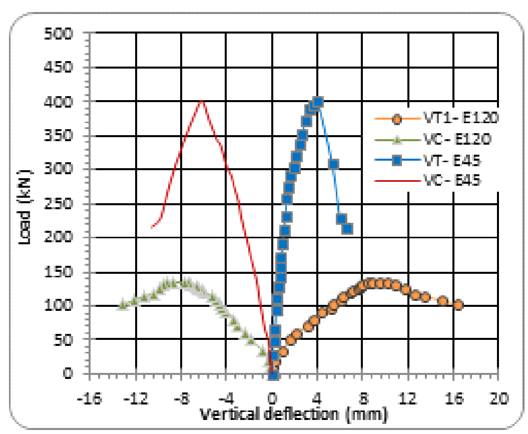
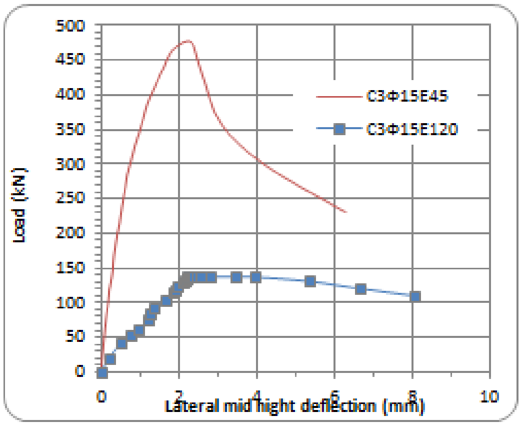


Figure 37. Load versus lateral mid-height deflection for columns C3Φ0E120 and C3Φ0E45



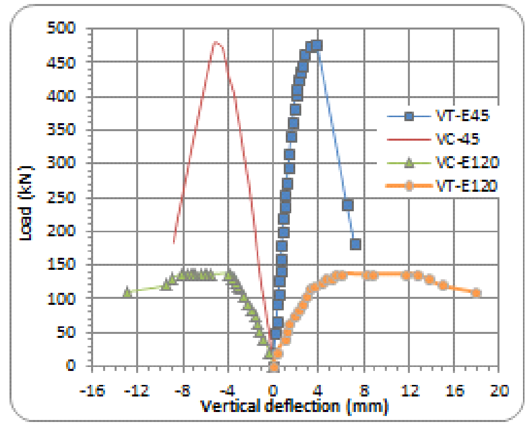
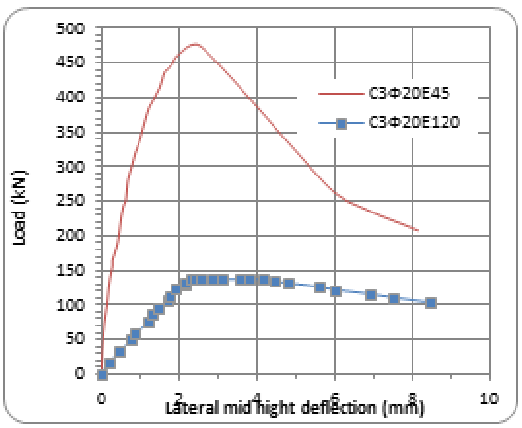


Figure 38. Load versus vertical deflection for columns C3Φ0E120 and C3Φ0E45

Figure 39. Load versus lateral mid-height deflection for columns C3Φ15E120 and C3Φ15E45



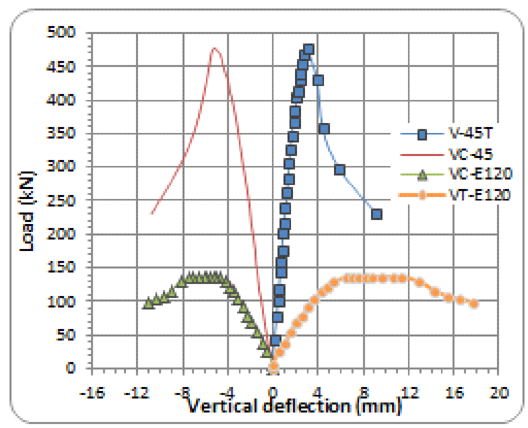
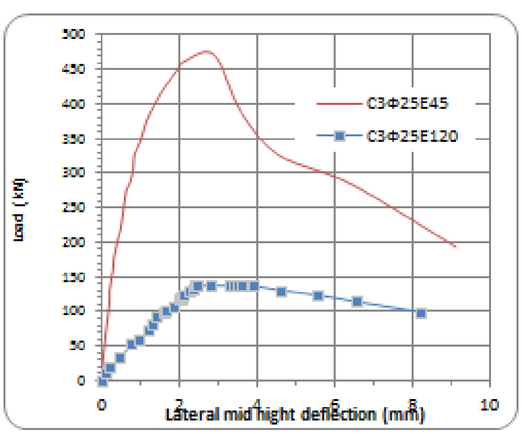


Figure 40. Load versus vertical deflection for columns C3Φ15E120 and C3Φ15E45

Figure 41. Load versus deflection for columns C3Φ20E120 and C3Φ20E45



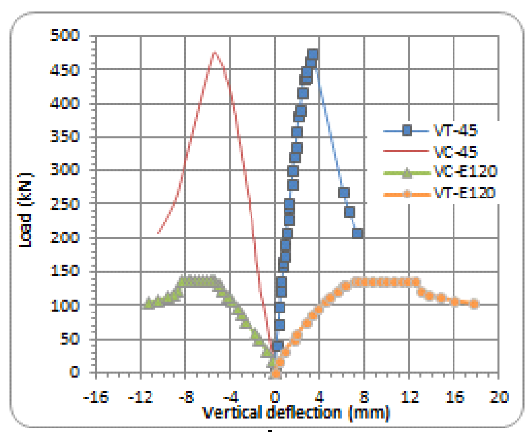


Figure 42. Load versus vertical deflection for columns C3Φ20E120 and C3Φ20E45

Figure 43. Load versus lateral mid-height deflection for columns C3Φ25E120 and C3Φ25E45

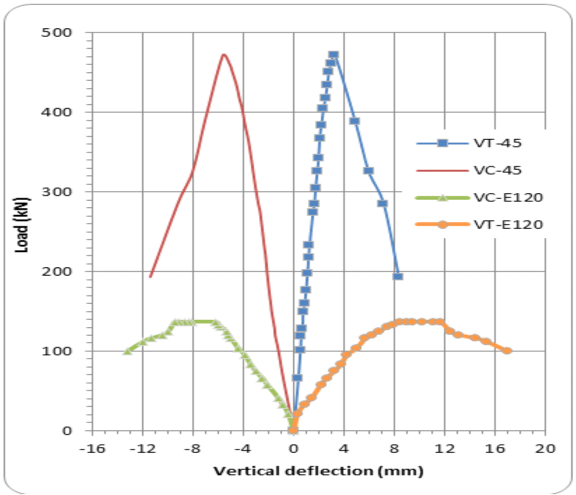


Figure 44. Load versus vertical deflection for columns C3Φ25E120 and C3Φ25E45.

Figure 45. Column C1Φ0E0 (group A), after testing

Figure 46. Column C1Φ20E0 (group A), after testing

(a) Compression face (b) Tension face

Figure 47. Column C1Φ15E45 (group A), after testing

(a) Compression face (b) Tension face

Figure 48. Column C3Φ20E45 (group B), after testing

(a) Compression face (b) Tension face

Figure 49.Column C1Φ20E120 (group A), after testing

(a) Compression face (b) Tension face

Figure 50. Column C3Φ15E120 (group B), after testing.